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Performance analysis of solar stills based on various factors affecting the productivity—A review

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ABSTRACT

Although, more than two-thirds of the Earth is covered by water, shortage of potable water is a serious issue that many countries suffer from. Furthermore, the worldwide rapid growth of industry and population has resulted in a large boom in demand for fresh water. The solar still, in many respects, is an ideal source of fresh water for both drinking and agriculture; it is one of the most important and technically viable applications of solar energy. There are many types of solar still; the simplest and most proven is the basin type. Investigations showed that the basin-type solar still has been found to be of limited performance. Numerous experimental and numerical investigations on basic types of solar still have been reported in various literatures. An extensive review for solar desalination systems has been carried out in this paper.

Contents

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1. Introduction

As early as in the fourth century, Aristotle described a method to evaporate impure water and then condense it for potable use. However, historically the earliest documented work on solar distillation was by Arab alchemists in the 16th century. The first water-distillation plant constructed was a system built as Las Salinas, Chile, in 1872. Nowadays solar stills are widely used in the solar desalination process.

Single basin solar still consists of a black painted basin contains brackish or sea water. This is enclosed in a completely airtight surface formed by a transparent cover. Incident solar irradiance passes through the transparent cover and is absorbed by the black basin plate. Consequently, water contained in the basin heated up and evaporates in the saturated conditions inside the still. Water vapor rises until they come in contact with the inner surface of the cover and condensed into pure water, run down along the cover bottom surface due to gravity and is collected using glass stopper. The construction of this type of still can easily be performed by local people using locally available materials.

People living in remote areas or islands, where fresh water supply by means of transport is expensive, face the problem of water shortage every day. Solar still presents some specific advantages for their use in these areas due to its easier construction using locally available materials, minimum operation and maintenance requirements and friendliness to the environment. It is really very fortunate that, in times of high water demand, solar radiation is also intense. It is therefore beneficial to exploit solar energy directly by installing solar stills. Two major advantages that favour the use of solar stills are: clean and free energy, and friendly to the environment. Their main disadvantage, however, is the lower output of distilled water in comparison with other desalination systems. The production capacity of a simple type still is in the range of 2–5 l/m^2/day only. This makes the system highly uneconomical. In solar desalination process, the productivity of the solar still is very less compared to other conventional desalination systems.

2. Factors affecting productivity of the solar still

The various factors affecting the productivity of solar still [1–3] are solar intensity, wind velocity, ambient temperature, water–glass temperature difference, free surface area of water, absorber plate area, temperature of inlet water, glass angle and depth of water. The solar intensity, wind velocity, ambient temperature cannot be controlled as they are metrological parameters. Whereas the remaining parameters, free surface area of water, absorber plate area, temperature of inlet water, glass angle and depth of water can be varied to enhance the productivity of the solar stills. By considering the various factors affecting the productivity of the solar still, various modifications are being made to enhance the productivity of the solar still. Murugavel et al. [4] reviewed the progress in improving the effectiveness of the single basin passive solar still. The main objective of this work is to review such modifications and its performance improvements in the solar still.

2.1. Free surface area of water

The evaporation rate of the water in the solar still is directly proportional to the exposure area of the water. Thus the productivity of the solar still increases with the free surface area of the water in the basin. To increase the free surface area of the water, sponges are used at the basin water.

Bassam et al. [5] used sponges to increase the free surface area of the water in the solar still as shown in Fig. 1. Due to capillary action, water is sucked by the sponges. The sponge cubes increase the surface area over which water evaporation occurs. The use of sponge cubes in the basin water resulted in a significant improvement in still production. Experiments were carried out with various sizes of the sponge cubes, sponge to basin water volume ratio and water depth. The optimal combination was: sponge cubes with 6 cm sides, 20% sponge to basin water volume ratio and 7 cm basin water depth. It was found that the increase in distillate production of the still ranged from 18% to 273% com-

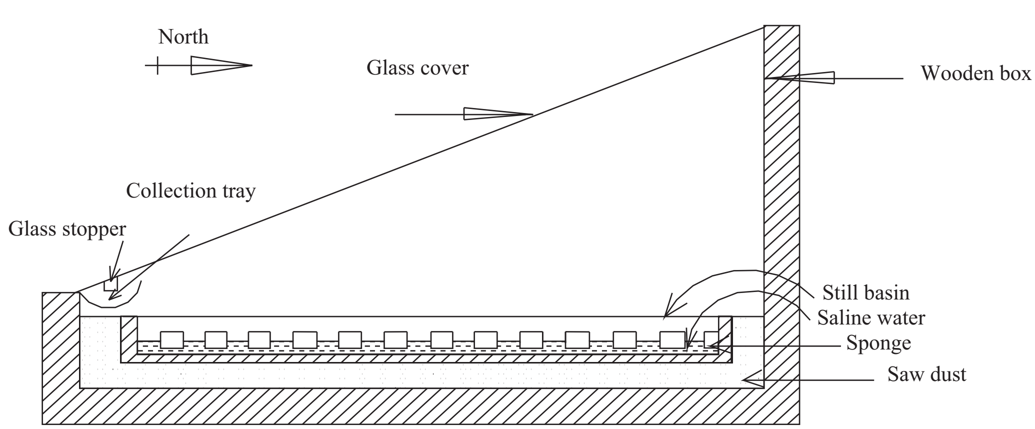

Fig. 1. Schematic diagram of the solar still with sponge cubes.

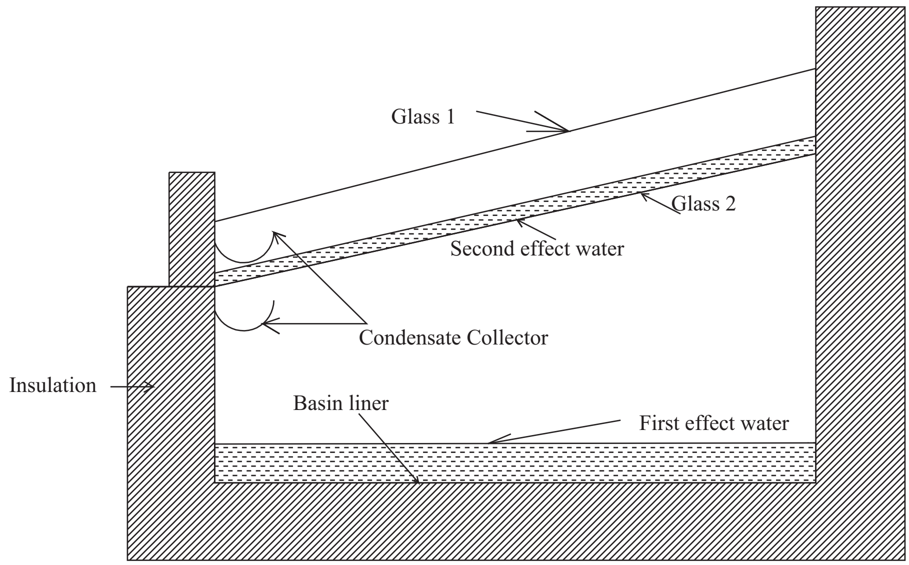

Fig. 2. Schematics of the regenerative solar still.

pared to an identical still without sponge cubes under the same conditions.

Velmurugan et al. [6–8] found that the productivity of the solar still increased by 15.3%, when the sponges are used in single basin solar still and stepped solar still integrated with fin.

2.2. *Water–glass temperature difference*

The yield of a solar still mainly depends on the difference between water and glass cover temperatures. The temperature difference between water and glass are acting as a driving force of the distillation process. Regenerative solar still [9], solar still with double glasses [10,11] and triple-basin solar still [11] were used to increase the temperature difference between glass and the water.

2.2.1. *Regenerative solar still with double glass*

The regenerative solar still consists of two basins, with provision for cooling water to flow in and out of the second effect as shown in Fig. 2. This arrangement has the advantages of increasing the temperature difference between water and glass cover in the first effect and utilizes the latent heat of water vapor condensing on the glass of the first effect to produce more fresh water in the second effect. The performance of the regenerative solar still is evaluated by comparison with the performance of the conventional still under the same weather conditions. The results show that the productivity of the regenerative still is 20% higher compared to the conventional still.

2.2.2. *Triple-basin solar still*

A triple-basin solar still [12] was fabricated by El-Sebaii. It consists of three basins namely, lower basin, middle basin and upper basin. Water was made available in all three basins. It was concluded that the productivity of the lower basin is higher than the productivities of the middle and upper basins during the day time, and this behavior is reversed overnight. Further, the total daily productivity of the system is maximum for the least water masses in the lower and middle basins without dry spots over the base of the each effect.

2.3. *Area of the absorber plate*

Productivity of the solar still increases with increase in absorber area. Fins are integrated with solar still to increase the absorber plate area.

Five rectangular solid fins [6] are integrated at the basin of the solar still as shown in Fig. 3. The area of the basin increases considerably. Experimental results showed that the average daily

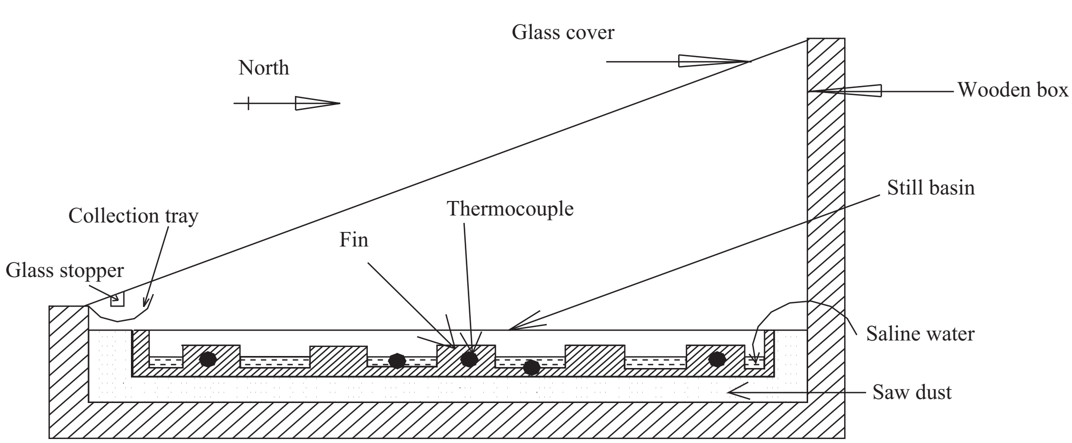

Fig. 3. Solar still integrated with fins.

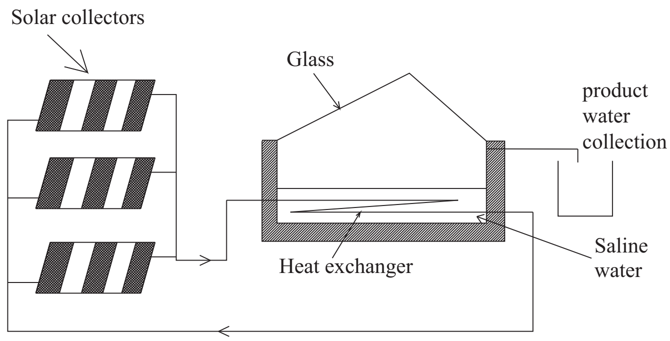

Fig. 4. Solar still coupled with collector.

production of distilled water in solar still increases by 30%, when fins are integrated in basin of the solar still.

2.4. Inlet temperature of water

The evaporation rate of saline water increases with the temperature of the saline water. Flat plate collector, storage tank, mini solar pond, multi-source, multi-use environment [13], greenhouse [14] and, multi-source, multi-use environment [15] heat pipe [16] are integrated with the solar still to increase the temperature of the solar still water. Higher energy may be required to increase the temperature of the entire solar still water. The evaporation rate is proportional with the temperature of the free surface area of the water only. So, baffle suspended absorber plates are used to increase the free surface area of the water.

2.4.1. Flat plate collector

A flat plate collector is integrated [17–21] with the solar still, to increase the temperature of the basin water. The preheated water from the solar collector was circulated by a tube through the basin water. The tube is acting as a heat exchanger and exchanging heat from the preheated water to the basin water as shown in Fig. 4. Thus the basin water gets heated. In an another arrangement, as shown in Fig. 5, the basin water is directly circulated through the flat plate collector. The various factors influencing the productivity of a multiple-effect diffusion-type solar still coupled with a flat plate collector and the effect of inclination of external flat plate collector of basin type still in winter were studied by Tanaka and Nakatake [22,23].

A single-stage basin-type solar still, a storage tank and a conventional flat-plate collector were connected together [24,25] in order to study the effect of augmentation on the still as shown in Fig. 6. The still inlet was connected to a locally made, fin-type collector such that its outlet was fed to the still basin instead of the common

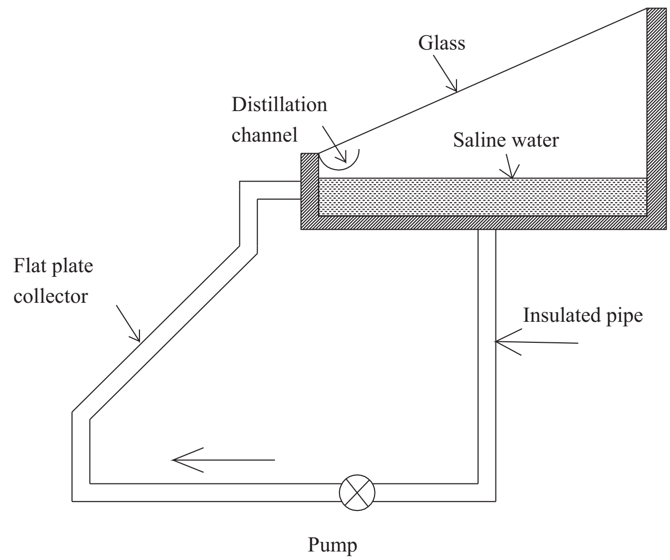

Fig. 5. Solar still coupled with flat plate collector.

storage tank. It was found that the mass of distilled water production using augmentation was increased by 231% in the case of tap water as feed and by 52% in the case of salt water as a feed.

2.4.2. Storage tank

An experimental evaluation of the behavior of a solar still is presented by Voropoulos et al. [26] in which a thermal storage tank with hot water is integrated as shown in Fig. 7. The integration of the storage tank is done in such a way that a compact solar distillation system is formed. This design leads to higher distilled water output due to higher basin water temperatures as a result hot storage tank water.

2.4.3. Mini solar pond

Velmurugan et al. [27,28] integrated a mini solar pond with single basin solar still as shown in Fig. 8. The mini solar pond supplied hot water to the solar still. Thus evaporation rate of the saline water in the solar still was augmented. The productivity of the solar still increases by 27.6% than the conventional solar still.

2.4.4. Baffle suspended absorber

As shown in Fig. 9, a single slope single basin solar still with baffle suspended absorber [29] was designed and fabricated, to decrease the preheating time of the basin water. The effect of vent area and water depth of upper and lower water column on the daily productivity of the solar still was studied. It was found that,

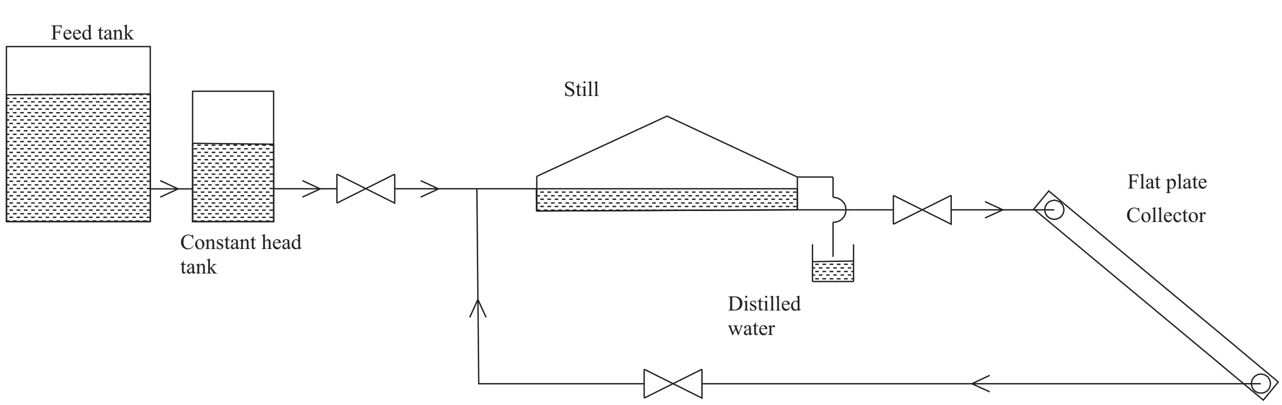

Fig. 6. Solar still coupled with tank and collector.

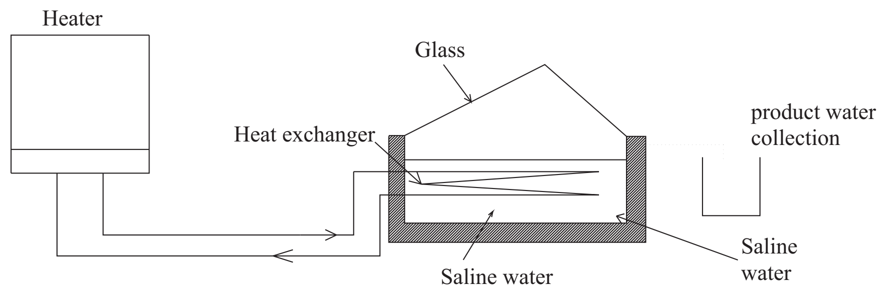

Fig. 7. Solar still coupled with a hot water storage tank.

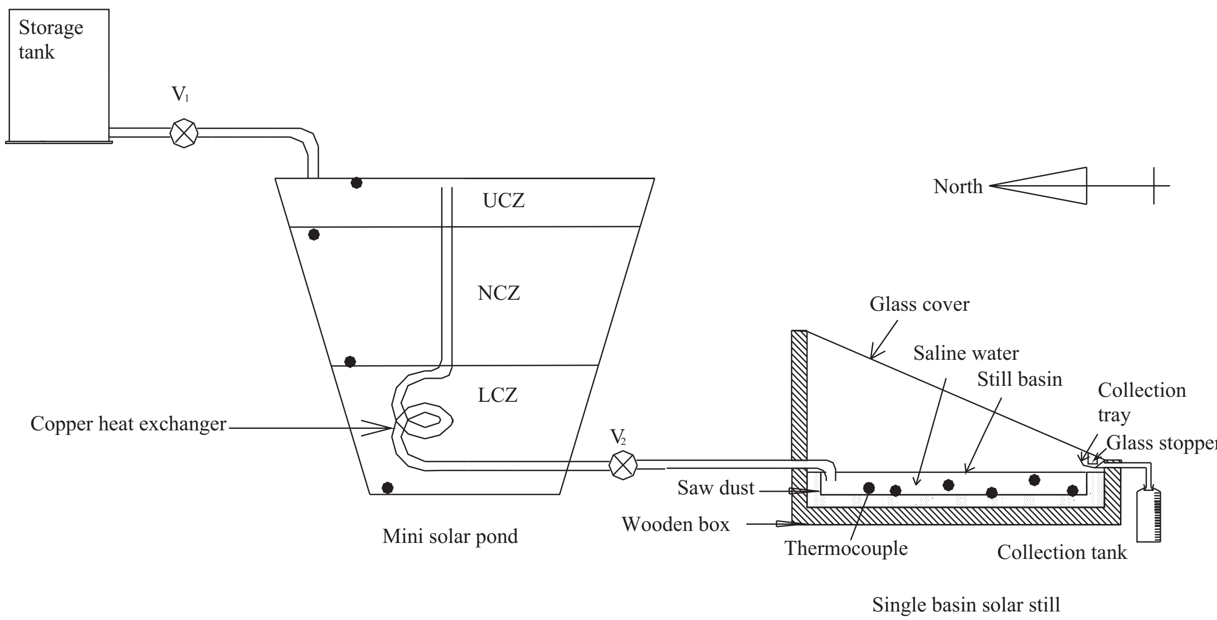

Fig. 8. Solar still integrated with a mini solar pond.

the daily productivity of the solar still is about 20% higher than that of conventional solar still when it is used with baffle suspended absorber.

2.4.5. *Floating perforated plate*

Productivity of the solar still increases with the saturation pressure of the water. The saturation pressure is determined by the temperature of the basin water. To increase temperature of the free surface area of the water, initially porous wick material was used. During the long run of experiments, the porous wick material would be clogged by accumulated salt. Therefore, floating perforated plates [30] are used to maintain film evaporation the still. The effect of using floating perforated black plate on the productivity process is investigated theoretically and experimentally at different brine depth under the same operating condition. It was found that using floating perforated aluminum plate in the solar still increase the solar still productivity by 15% for a brine depth of 3 cm and 40% for a brine depth of 6 cm.

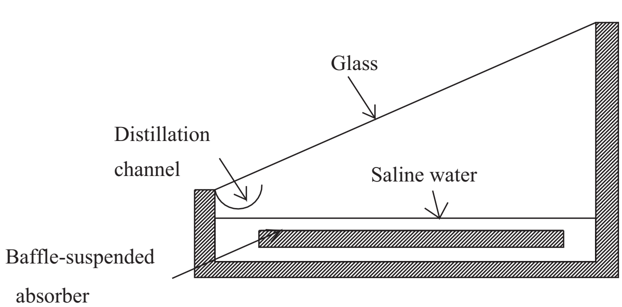

Fig. 9. Solar still with baffle suspended absorber.

2.5. *Glass angle*

Singh and Tiwari [31] found that the annual yield of the solar still was maximum when the condensing glass cover inclination is equal to the latitude of the place.

2.6. *Depth of water*

It has been reported that the yield is maximum for the least water depth. While maintaining minimum depth in the solar still, dry spot may occur. So, it is very difficult to maintain minimum depth in the solar still. Wick type solar stills [32,33], a plastic water purifier [34] and stepped solar still [8,35] were developed. The effect of various depth of water [36] in the solar still is verified by Khalifa and Hamood. Extreme operating condition in shallow solar stills was studied by Porta et al. [37]. Murugavel et al. [38,39] studied an experimental study on single basin double slope simulation solar still with thin layer of water in the basin.

2.6.1. *Wick type*

Minasian and Al-Karaghouli [32] connected a wick type solar still with a conventional basin-type solar still. The hot waste brine

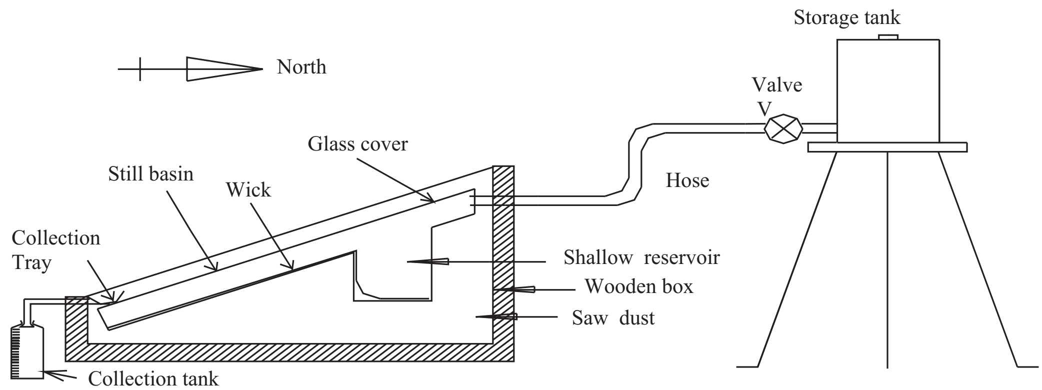

Fig. 10. Wick type solar still.

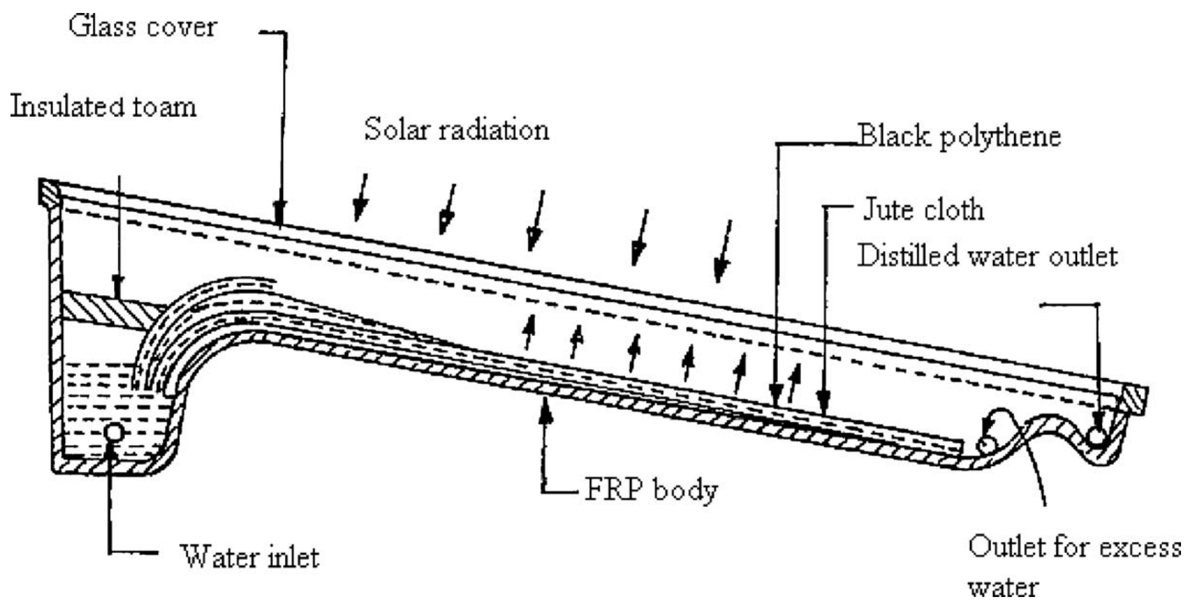

Fig. 11. Multi-wick type solar still.

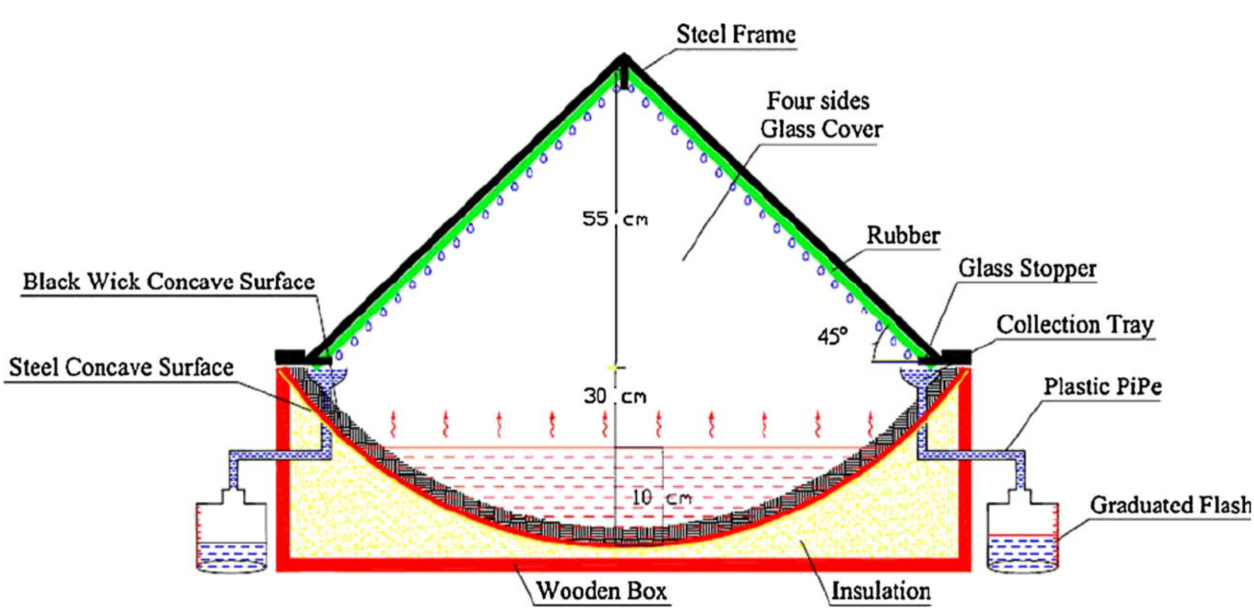

Fig. 12. Schematic diagram of concave wick solar still.

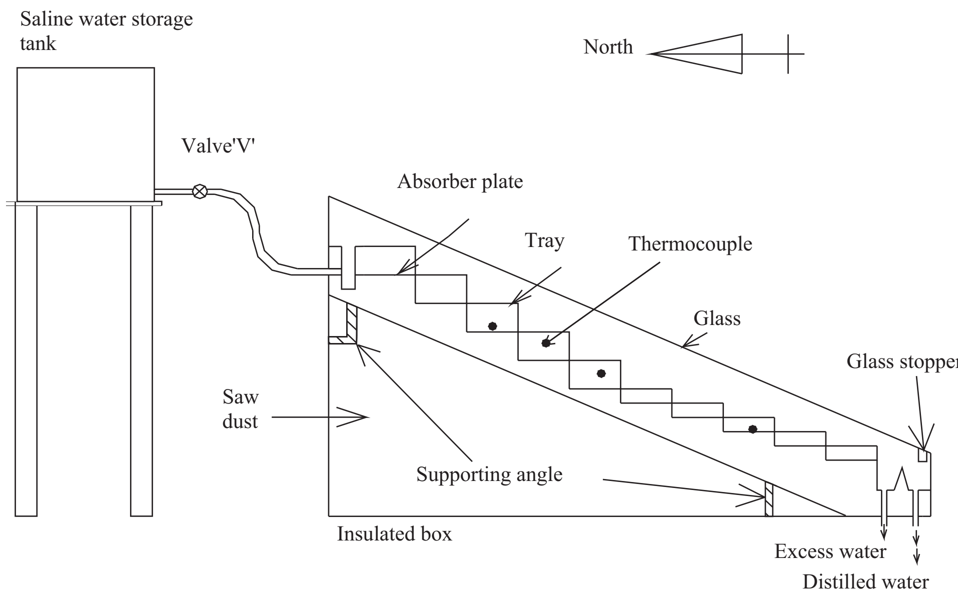

Fig. 13. Schematic diagram of a stepped solar still.

leaving the wick-type would feed the basin type in order to extract the energy contained in the lost hot drainage water and thus increase the productivity of the wick-type solar still. Fig. 10 shows the schematic diagram of the experimental set-up. Two types of solar stills were investigated. These were: a conventional basin-type and wick-basin type solar still. The total yearly amounts of distilled water indicate that the wick-basin type could produce 85% more than the basin type and 43% more than the wick type solar still.

In multi-wick solar still [33], jute cloth with different lengths are used. One end of a wet jute cloth pieces (porous fiber) are dipped into a water reservoir while the other ends are spread over the absorber basin as shown in Fig. 11. The jute cloth pieces are blackened and placed one upon the other, separated by polythene sheets. Here the wet piece of jute cloth forms the water surface in the still. It could attain a higher temperature due to its negligible heat capacity. This leads to rapid evaporation of water.

Surfaces used for evaporation and condensation phenomena play important roles in the performance of basin type solar still. As shown in Fig. 12, a concave wick surface [40] was used for evaporation, whereas four sides of a pyramid shaped still were used for condensation. Use of jute wick increased the amount of absorbed solar radiation and enhanced the evaporation surface area. A concave shaped wick surface increases the evaporation area due to the capillary effect. Results show that average distillate productivity in day time was 4.1 l/m^2 and a maximum instantaneous system efficiency of 45% and average daily efficiency of 30% were recorded. The maximum hourly yield was 0.5 l/h m^2 after solar noon. An estimated cost of 1 l of distillate was 0.065$ for the presented solar still.

2.6.2. *Plastic solar water purifier*

Ward [34] designed a solar water purifier, which consists of a plastic sheet and a glass window. The author formed the plastic into an array of interconnected square cells which contain impure water. In their experimental set-up there were no filters, no electronics, no moving parts and cleaning was also rarely needed. It was light weight, cheap strong, durable and cheap. It can be used in any sunny location on earth.

2.6.3. *Stepped solar still*

While maintaining minimum depth in the solar still dry spots are formed. So, maintaining minimum depth in the solar still is very difficult. To overcome this problem, a solar still with stepped structured absorber plate was designed and fabricated by Velmurugan et al. [8,35]. As shown in Fig. 13, there are 50 trays in the solar still. The sizes of the trays are 99 mm × 99 mm cross-section with different depth. Experiments were carried out with fins and sponges in the stepped solar still to enhance its productivity.

3. Other methods

Reflectors, condenser, vacuum technology, combined stills, asphalt basin liner and sprinkler and sun tracking systems are used to maximize the yield of the solar still. Also energy storage materials like black rubber, gravel and metallic wiry sponges are used for enhancing the productivity of the solar still. The effect of using different designs of solar stills on water distillation was studied by Al-Hayek and Badran [41].

3.1. *Reflectors*

Tanaka and Nakatake [42] proposed a geometrical method to calculate the solar radiation reflected by the internal and external reflectors and then absorbed on the basin liner. The schematic diagram for the set is shown in Fig. 14. They found that the internal and external reflectors remarkably increase the distillate productivity by 48%.

3.2. *Condenser*

An external condenser [43] is attached with a solar still as shown in Fig. 15 to enhance the productivity of the solar still. The condensation occurs due to the temperature difference not only on the glass surface but also on the four sidewalls, which can be cooled by water circulation through tubes attached on the wall surface for efficiency enhancement. Such an arrangement [44] is made to enhance the productivity of the solar still as shown in Fig. 16. The

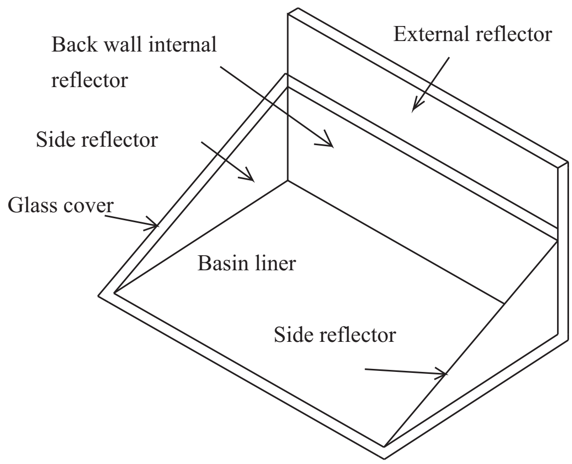

Fig. 14. Solar still with reflectors.

maximum daily production of the solar still was about 1.4 l/m^2/day, and its efficiency was about 30% with corresponding average solar insolation of 28 MJ/day. The condensate water quality was analysed and was found to be comparable with water quality standards and against rainwater and mineral water. Increased cooling on the wall surface was observed enhancing the condensation process. To comprise in a nutshell, conclusions can be drawn that the utilization of solar energy in purifying water offers a good recommendation not only on the environmental aspect but also on the sanitation. Performance study on solar still with enhanced condensation [45] was studied by Kumar and Bai

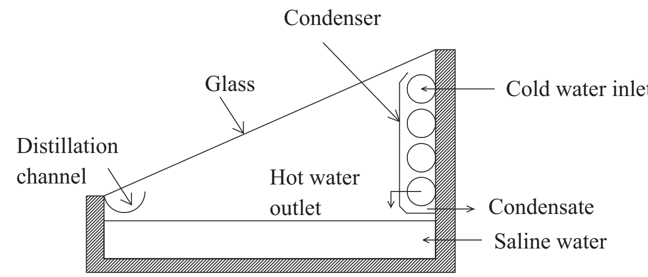

Fig. 16. Solar still with internal condenser.

3.3. Energy storing materials

To store the thermal energy in solar still, some energy storing materials are used. Black rubber, gravel, metallic wiry sponges and surfactant additives are some of the energy storing materials used in solar still.

3.3.1. Black rubber

The influence of the variation of the rubber sheet thickness on the still productivity is investigated by Nafey et al. [46]. The experimental results showed that black rubber of 10 mm thick improves the productivity by 20% at the conditions of 60 l/m^2 brine volume and 15° glass cover angle.

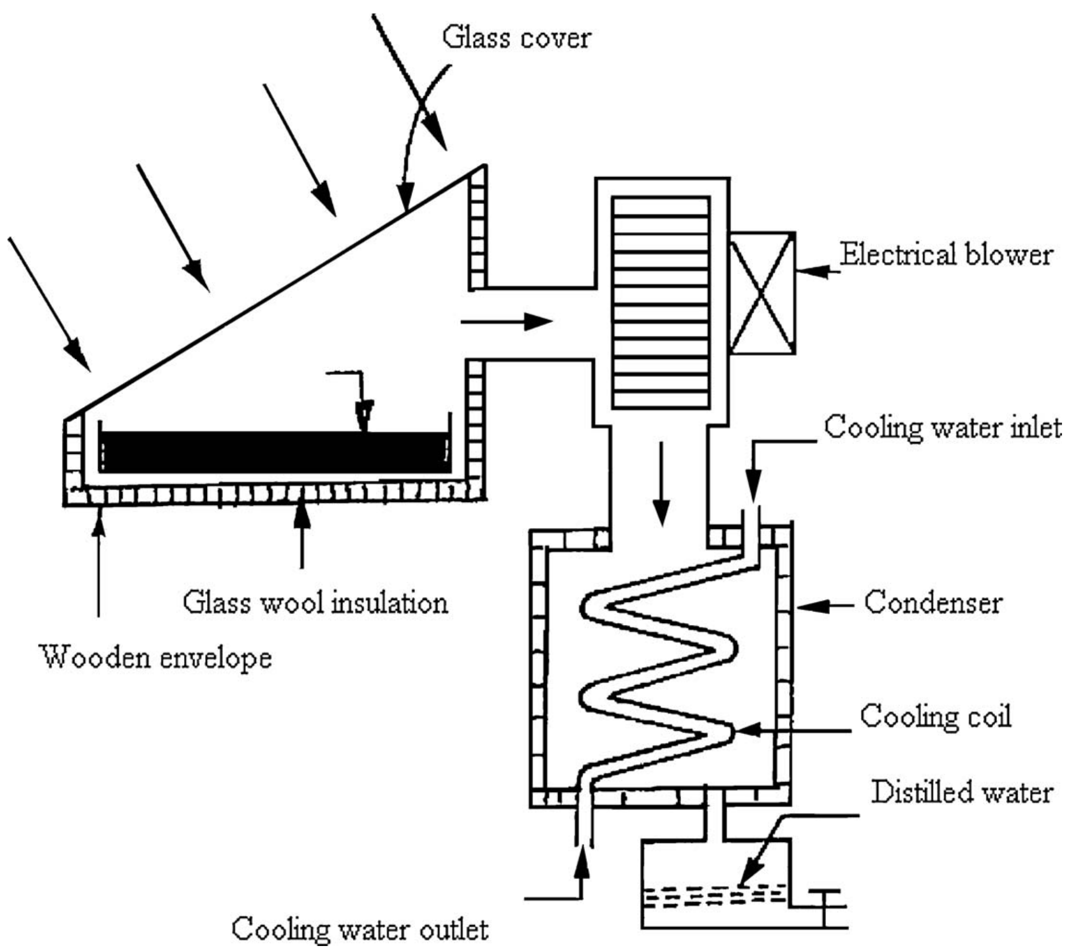

Fig. 15. Solar still with external condenser.

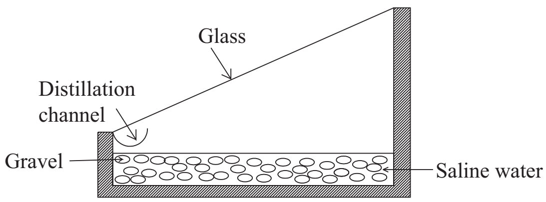

Fig. 17. Solar still with gravel.

3.3.2. Gravel

Nafey et al. [46] studied the influence of black gravel on the productivity of the solar still. The solar still with gravel is as shown in Fig. 17. Using black gravel of 20–30 mm size improves the productivity by 19% at the condition of 20 l/m^2 brine volume and 15° glass cover angle. Also Velmurugan et al. [47] added pebbles in the solar still and found that the productivity increased by 20% than the conventional solar still.

3.3.3. Metallic wiry sponges

Different types of absorbing materials like metallic wiry sponges (coated and uncoated) and black volcanic rocks [48] are used to study their effect on the yield of solar stills as shown in Fig. 18. The results showed that the uncoated sponge has the highest water collection during day time, followed by the black rocks and then coated metallic wiry sponges. On the other hand, the overall average gain in the collected distilled water taking into the consideration the overnight water collections were 28%, 43% and 60% for coated and uncoated metallic wiry sponges and black rocks, respectively.

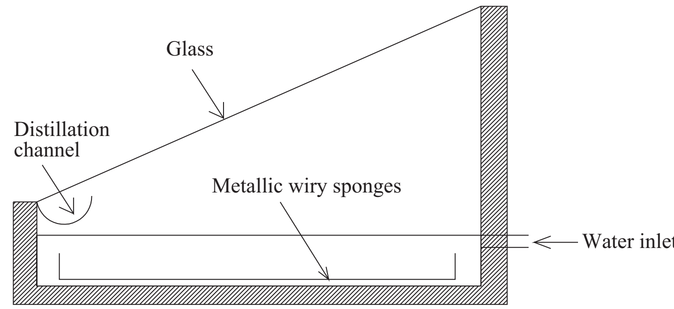

Fig. 18. Solar still with metallic wiry sponges.

3.3.4. Surfactant additives

The presence of surfactant additives [49] in water is found to enhance the boiling heat transfer significantly. The effect of using a surfactant as sodium lauryl sulfate (SLS) in relatively small dosages of concentration with a small size unit of solar water distillation process is investigated.

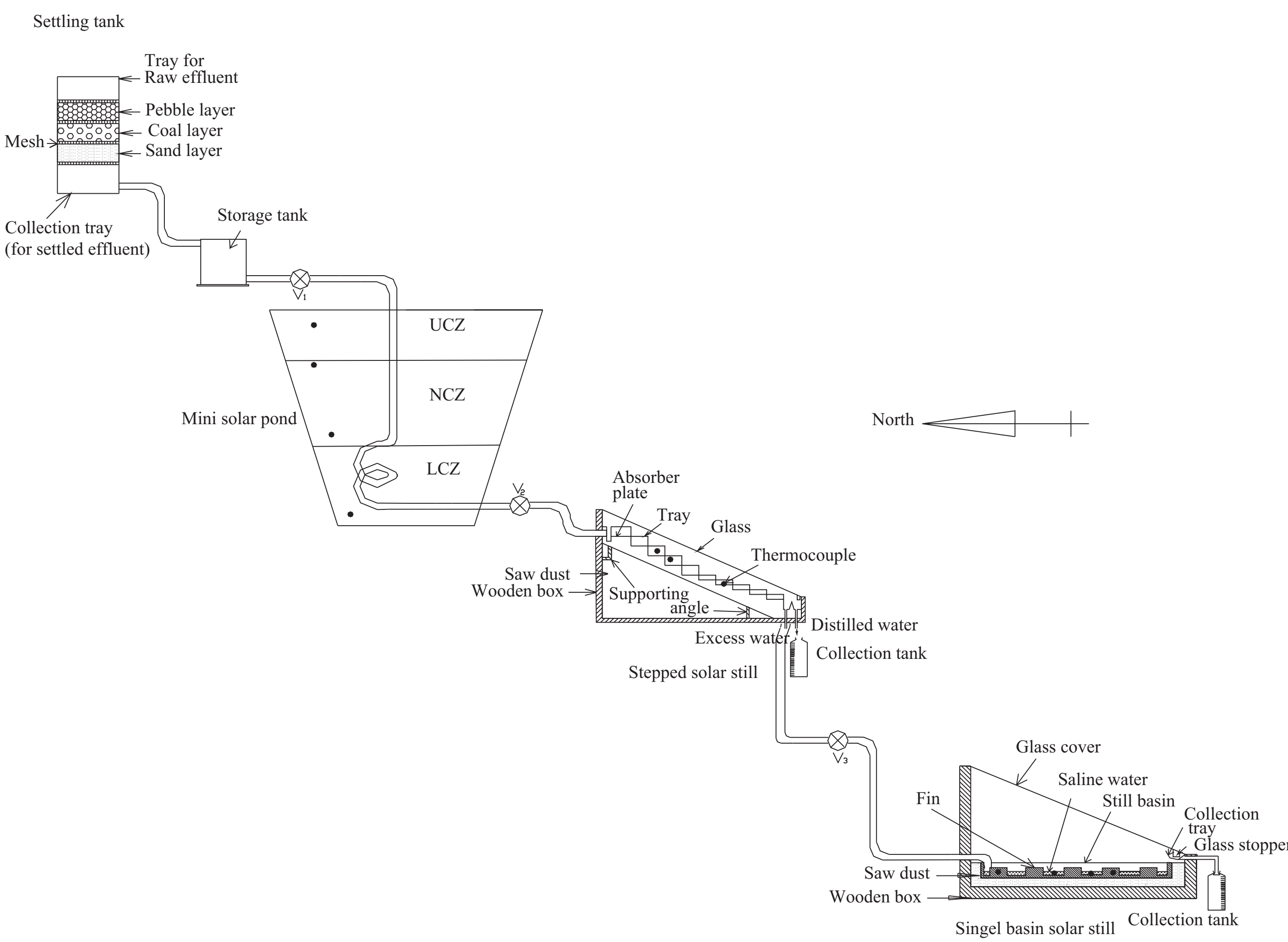

Fig. 19. Schematic diagram of combined stills.

3.4. Vacuum technology

The effect of vacuum inside the still is to avoid any heat transfer due to convection in the still. The heat loss from the water in an insulated still is due to evaporation and radiation only. In the presence of vacuum, the effect of the non-condensable gas, which reduces the rate of condensation, was also avoided. Hussaini and Smith [50] studied the effect of applying vacuum inside the solar still. It was found that the solar still's water productivity increased by 100% when vacuum was applied.

3.5. Combined stills

Velmurugan et al. [47,51] integrated a mini solar pond, a stepped solar still and a single basin solar still as shown in Fig. 19. They were used this experimental set-up for effluent desalination process. Initially, water from the effluent settling tank is allowed to pass through the mini solar pond. While passing through the mini solar pond, it is getting heated. The hot effluent water enters into stepped solar still and the distilled water is produced. The excess water from the stepped solar still enters into the single basin solar still. Thus, distilled water is produced in both single basin solar still and stepped solar still.

3.6. Asphalt basin liner and sprinkler

It can be highlighted that when the asphalt basin liner was used the productivity increased by 29%, this may be due to the high absorbency of the asphalt compared to the black paint, and also the asphalt liner will act as an insulator in the same time. Another enhancement in productivity of the still can be increased by introducing a sprinkler (cooling film) to the outer layer of the glass cover of the still; this will increase the productivity from the latter case by another 22%.

3.7. Sun tracking system

A computerized sun tracking device was used for rotating the solar still with the movement of the sun [52]. A comparison between fixed and sun tracked solar stills showed that the use of sun tracking increased the productivity for around 22%, due to the increase of overall efficiency by 2%. It can be concluded that the sun tracking is more effective than fixed system and it is capable of enhancing the productivity.

4. Conclusion

The various research work done on solar still to improve its productivities are reviewed. The important points are highlighted below.

- Free surface area of water, water glass temperature difference, absorber plate area, temperature of inlet water, glass angle and depth of water are the various operational parameters, affecting the productivity of the solar still. The parameters are changed by modifying the solar still to enhance the productivity of the solar still.
- Sponges are used to increase the free surface area of the water in the solar still.
- Regenerative solar still, triple basin solar still and solar still with double glasses are used to increase the temperature difference between water and glass.
- Fins are used to increase the area of the absorber plate.
- Flat plate collector, storage tank, mini solar pond, floating perforated plate and baffle suspended absorber are used to increase the inlet temperature of the water.
- It was found that the annual yield of the solar still was maximum when the condensing glass cover inclination is equal to the latitude of the place.
- Wick type solar stills, a plastic water purifier and stepped solar still were developed to maintain minimum depth in the solar still.
- Apart from this, reflector, condenser, black rubber, black gravel, metallic wiry sponges, vacuum technology, multi-use multi-source environment, combined stills, asphalt basin liner, sprinkler and surfactant additives are also used to enhance the productivity of the solar still.

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